Performance Analysis of In-Band Full Duplex Collision and Interference Detection in Dense Networks

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***Abstract*—The densification of wireless networks that contend for a shared medium, demands improved MAC solutions that can reduce the energy cost of packet collisions. In this paper we analyze a novel in-band full duplex collision and interference detection scheme for dense networks, studying the energy savings that it can bring with respect to the performance of half duplex communications. Under a high external interference scenario, results show that the proposed full duplex scheme is more energy-efficient than half duplex transmissions for any network density. When the interference is low, the full duplex scheme provides energy gains when the number of contending devices is above a critical value. Expressions for calculating this critical number of devices are provided, showing that it is smaller when the likelihood of collisions increases. In the studied cases, results show the energy savings grow exponentially with the density of the network.**

I. Introduction

The widespread emergence of wireless technologies and exponential growth of mobile data traffic is causing a progressive densification of the existing wireless networks [1]. In these *ultra dense networks* a large number of devices have to share limited spatial and spectral resources, introducing unprecedented requirements in terms of spectral sharing and interference management [2]. Moreover, most of these devices are mobile and therefore battery-limited, introducing additional constraints on the energy-efficiency of the system [3]. These requirements have renewed the interest in finding novel MAC solutions that can reduce the energy and spectrum cost of packet collisions.

Most MAC protocols, like in IEEE 802.11 [19] and IEEE 802.15.4 [18], use Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) to allow multiple nodes to access the medium. However, this scheme is not well suited for dense networks, where the large number of nodes generate an important number of packet collisions [4]. These collisions reduce the effective throughput of the network and increase the energy spent by each node per successfully transmitted message. One could tune the CSMA/CA parameters to decrease the number of collisions, however this also increase the backoff delay, resulting in a lower throughput.

One way of reducing the impact of collisions without increasing the backoff delay, is to introduce Collision Detection (CSMA/CD). This scheme allows the transmitting nodes to detect collisions in real time and abort the corresponding ongoing transmission, reducing the time and radiated energy that is lost in each collision. Although promising, the implementation of this technique in wireless systems is challenging, mainly due to the large power difference between the self-transmitted signal and the incoming signal [5].

A novel way of implementing CSMA/CD in wireless networks is provided by in-band full duplex (IBFD) wireless communication, as proposed in our previous work [6]. This attractive solution allows two nodes to communicate with each other at the same time and on the same frequency. IBFD requires the self-transmitted signal to be canceled both in the analog and digital domain [5]. In-band full duplex is feasible without losing any SNR on the link, as sufficient self-interference cancellation can be achieved by applying state of the art techniques [7], [8]. It has been shown that IBFD can provide important throughput gains, as it can almost double the bidirectional throughput without increasing the spectrum usage [9].

Although the throughput gains that IBFD provides are well understood, its potential for increasing the energy and spectrum efficiency of dense wireless communications has only started to be explored. The energy efficiency achievable in a cellular system where the base station is equipped with in-band full duplex capabilities is studied in [10]. Whereas [11] analyzes the energy efficiency of full duplex equipped relay nodes. Also in [12] full duplex equipped relay nodes are used to design an energy-efficient power allocation strategy. Although related, the scope of these works is fundamentally different from our approach, as they don't consider the case where the end devices that are contending for the shared spectrum are equipped with full duplex capabilities.

In this work an analytical model of an unslotted in-band full duplex CSMA/CD MAC scheme (denoted in the following as FD-CSMA/CD) is presented, following [6] where a slotted version was introduced and analyzed only through simulations. In contrast, here we propose an analytical model for studying how the energy consumption of FD-CSMA/CD scales with the number of wireless devices that share the medium. We also explore the conditions under which it is more energy-efficient than half duplex (denoted as CSMA/CA) transmissions.

The rest of the paper is structured as follows. Section II presents a review on collision detection, followed by a description of FD-CSMA/CD in Section III. Section IV presents our link layer transmission cost model. Section V analyses the energy gains provided by the FD-CSMA/CD scheme, which are later verified in Section VI. Finally Section VII presents our conclusions.

II. Related work on collision detection

The collisions that arise when distributed nodes have to contend for a shared medium are one of the biggest problems in dense wireless networks, where coordination between the many nodes is expensive or even impossible. Several solutions have been proposed to this problem in the literature. One of these proposals, CSMA/CN [13], follows the standard CSMA protocol to acquire the medium but the receiver notifies the transmitter using a distinct signature when a collision occurs. The signature is unique for every transmitter, which correlates the incoming signal with this signature. Upon detecting a peak in the correlation the transmitter stops its transmission. Just as with in-band full duplex, the self transmitted signal needs to be sufficiently suppressed to allow the correlator to detect the signature. CSMA/CN improves throughput up to 50% compared to normal IEEE 802.11. However, CSMA/CN does not solve the hidden terminal problem but only copes with the consequences, i.e. it aborts the transmission.

To overcome the hidden terminal problem, several solutions are proposed. The first one is the IEEE 802.11 DCF technique, which uses in-band control frames to avoid hidden terminals. The transmitting node will first send a Request to Send (RTS) packet to the receiver and wait for a Clear to Send (CTS) packet, before transmitting its data packet. This solves the hidden terminal problem but introduces overhead and delay. Another solution is to use an out-of-band control channel, like in Busy Tone Multiple Access (BTMA) [14]. This scheme divides the available bandwidth into a data channel and a busy-tone channel. Whenever a node wants to transmit a packet, it will first sense the busy-tone channel to check if the medium is free. If the medium is free, the node will both transmit a busy tone and the data packet. BTMA adds no overhead to the transmission but uses extra bandwidth for the control channel and needs two transceivers on different frequencies.

A MAC protocol that combines both of these hidden terminal solutions is presented in [15]. Here pulses in an out-of-band control channel are used for collision detection, together with a CTS signal in the control channel to mitigate hidden terminals. This protocol solves the hidden terminal problem without adding overhead and uses only a small amount of extra bandwidth. However, still two transceivers on different frequencies and two antennas are needed. It can also only detect collisions at the transmitter side of nodes following the same protocol. Collisions with standard Wi-Fi nodes for example cannot be detected and the packet is still transmitted in full. Therefore it does not solve the collision and interference detection problem completely.

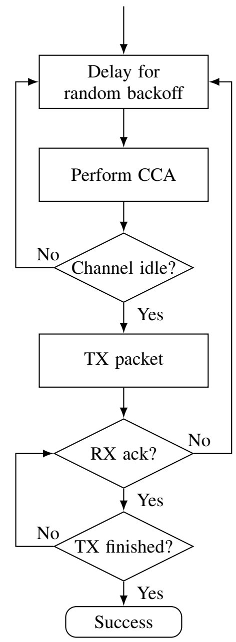

Fig. 1. Flowchart of the FD-CSMA/CD algorithm

III. FD-CSMA/CD MAC scheme

The proposed unslotted MAC scheme uses in-band full duplex to implement both collision detection and avoidance without any overhead or need for extra bandwidth, while also solving the hidden terminal problem. A detailed description of a similar but slotted algorithm can be found in [6]. In the scheme we assume it is possible for the receiver to know when a collision or interference occurs by using physical layer information. For example in [16], information like the Link Quality Indicator and the Packet Error Rate is used to detect interference. These techniques can identify interference with an accuracy of 80%.

The flowchart of FD-CSMA/CD is shown in Fig. 1, it is very similar to CSMA/CA and therefore fully backwards compatible. A FD-CSMA/CD node will first delay for a random time to avoid collisions with other nodes. Then it performs a Clear Channel Assessment (CCA). If the channel is idle, it will transmit its packet. The receiving node will immediately acknowledge the reception of this packet if the header is correctly received. It will keep on transmitting this acknowledgment as long as it hasn't detected any collision or interference. The transmitting node will keep transmitting as long as it receives the acknowledgment.

The full duplex collision detection scheme is shown in Figure 2. Whenever the receiving node detects a collision or interference, it stops transmitting the acknowledgment. This will cause the transmitting node, who is listening to the acknowledgment, to stop its transmission, freeing up the medium. FD-CSMA/CD allows to almost immediately detect collisions or interference at the receiver and because of the immediate acknowledgment, which acts as a continuous CTS, it also solves the hidden terminal problem. All nodes in range of

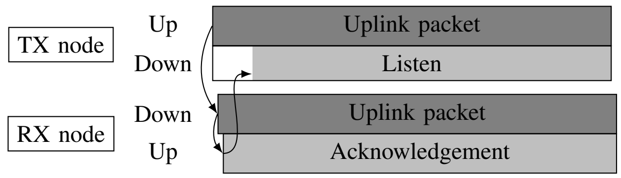

Fig. 2. Full duplex collision detection (Source: [6])

the receiving node will sense the immediate acknowledgment and defer their transmission until the channel is clear, i.e., the receiving node has stopped transmitting the acknowledgment.

IV. Link layer transmission cost model

In this section we determine the total amount of energy that is required to successfully transmit one bit of data using the proposed FD-CSMA/CD scheme. The present work focuses on the energy consumption of a node that is transmitting data, leaving the analysis of a receiver node for a future work due to space limitations. An important case where this approach is relevant are sensor networks with star topology, where battery-powered sensor nodes transmit data to a central node which has an AC power supply and hence is not energy-constrained.

First, Section IV-A presents a MAC layer performance model, focusing both on throughput and energy, for a transmitter that uses a CSMA/CA transmission scheme. Then, Section IV-B discusses the main differences that characterize our proposed FD-CSMA/CD scheme from a throughput and energy point of view. The modeling is based on the framework presented in [17]. Both are compared in Section VI. Table I gives an overview of all the symbols used in this and the following section.

TABLE I
Key performance model symbols

$\bar{\rho}_c^{HD}, \bar{\rho}_c^{FD}$	Average number of retransmissions due to collisions for half and full duplex
$\bar{\rho}_i$	Average number of retransmissions due to inference from other networks (given no collisions)
$\bar{\tau}_d$	Average number of transmission trials due to decoding errors (given no collisions and interference)
γ_c	Fraction of time per bit required to detect a collision
γ_i	Fraction of time per bit required to detect interference
q_c	Collision rate
q_i	Interference rate
$\bar{P}_f$	Mean frame error rate (given no collisions and interference)

A. Performance of CSMA/CA

We consider unacknowledged packet-switched transmissions, where it is assumed that all frames are always detected. Under these assumptions, the total energy required by a node for sending one bit of data successfully using half duplex (HD) CSMA/CA transmissions can be expressed as

$$\bar{\mathcal{E}}_T^{HD} = \left[(P_{el,tx} + P_{PA})\, T_b \right] \bar{\tau}^{HD} \quad . \tag{1}$$

Above, T_b is the average air time per payload bit, P_{PA} is the power consumed by the power amplifier (PA) and $P_{el,tx}$ is the total power consumed by the remaining baseband and radio-frequency electronic components that perform the transmission. Finally, $\bar{\tau}^{HD}$ is the average number of transmission trials required until a frame is decoded without errors in the receiver, which can be decomposed as

$$\bar{\tau}^{HD} = \bar{\tau}_d + \bar{\rho}_i + \bar{\rho}_c^{HD} \quad , \tag{2}$$

where $\bar{\rho}_c^{HD} \geq 0$ is the average number of retransmissions due to collisions with transmissions from the same network, $\bar{\rho}_i \geq 0$ is the average number of retransmissions due to interference with transmissions from other networks under the condition of no collisions, and $\bar{\tau}_d \geq 1$ is the average number of *transmission trials* needed for achieving a correctly decoded frame conditioned on the event of a reception without collisions or interference.

For finding an explicit expression for T_b, let us define $r = k/n$ as the code rate, where n is the number of bits per codeword and $n-k$ is the number of added redundancy bits. Then, each physical-layer frame carries L_H bits of header and a payload composed by rL_P bits of data and $(1-r)L_P$ additional bits for coding. The total duration of a frame consists of T_P seconds for transmitting the payload, T_H seconds for transmitting the header and T_O seconds for the transmission of overhead signals for acquisition and tracking (channel estimation, synchronization, etc.). The average air time per payload bit in a frame is

$$T_b = \frac{T_P + T_H + T_O}{rL_P} \quad . \tag{3}$$

Let us define R_s as the physical layer symbol rate and $b = \log_2 M$ as the number of bits per symbol. By considering that header bits are sent using a binary modulation, and noting that $L_P/T_P = bR_s$, then one can express T_b as

$$T_b = \frac{1}{rR_s}\left(\frac{1}{b} + \frac{L_H}{bL_P} + \frac{L_O}{L_P}\right) \quad , \tag{4}$$

where $L_O = T_O/R_s$ is the total overhead measured in equivalent bits.

B. Performance of FD-CSMA/CD

There are two major features that distinguish our proposed FD-CSMA/CD from CSMA/CA communications from an energy consumption point of view.

First, collisions are detected before the end of the transmission of the full frame. Remember from Section III that there are no hidden terminals, meaning that every node will be aware of an ongoing transmission, in this case collisions can only occur in the beginning of the transmission. So if there are only transmissions coming from the same network, the total time per payload bit required for detecting a collision is equal to the time required to decode the header, this is given by

$$T_b^{col} = \frac{1}{rR_sL_P}\left(\frac{L_H}{b} + L_O\right) \quad . \tag{5}$$

Using (4) and (5), one can also rewrite $T_{\mathrm{b}}^{\mathrm{col}} = \gamma_{\mathrm{c}} T_{\mathrm{b}}$ with $\gamma_{\mathrm{c}} = (L_{\mathrm{H}} + bL_{\mathrm{O}})/(L_{\mathrm{P}} + L_{\mathrm{H}} + bL_{\mathrm{O}})$, which is a parameter that represents the fraction of time per bit that is required to detect a collision. Note that $0 < \gamma_{\mathrm{c}} \ll 1$, as in general L_{P} is much larger than L_{H} and L_{O}. On the other hand, for the case of collisions due to interference coming from other networks one can define $T_{\mathrm{b}}^{\mathrm{i}}$ to be the average total time per payload bit required for detecting the interference, and introduce an analogous parameter $0 < \gamma_{\mathrm{i}} < 1$ which satisfies $T_{\mathrm{b}}^{\mathrm{i}} = \gamma_{\mathrm{i}} T_{\mathrm{b}}$. As events in different networks are usually uncorrelated the interference can interrupt the transmission at any point of the frame; hence it can be assumed that $\gamma_{\mathrm{i}} \approx 1/2$.

Secondly, in an in-band full duplex system the receiver radio in the transmitter is active during the transmission of the frame for detecting collisions and interference and receiving feedback packages. As some of the electronic components can be shared between the transmitter and receiver front-ends, the power consumption of the electronic components is smaller than $P_{\mathrm{el,tx}} + P_{\mathrm{el,rx}}$, with $P_{\mathrm{el,rx}}$ equal to the total power consumed by the receiver. Hence, by denoting the power consumption of the electronic components of a full-duplex transceiver as $P_{\mathrm{el,FD}}$, we introduce the parameter $\alpha > 0$ such that the following condition holds:

$$P_{\mathrm{el,FD}} = P_{\mathrm{el,tx}} + \alpha P_{\mathrm{el,rx}} \ . \tag{6}$$

Although IBFD requires some extra circuitry to cancel the self-interference, this can be incorporated in α.

Considering the previous observations, the energy consumption per goodbit of our proposed FD-CSMA/CD scheme can be expressed as

$$\bar{\mathcal{E}}_{\mathrm{T}}^{\mathrm{FD}} = \left[P_{\mathrm{el,tx}} + P_{\mathrm{PA}} + \alpha P_{\mathrm{el,rx}}\right] T_{\mathrm{b}} \left(\bar{\tau}_{\mathrm{d}} + \gamma_{\mathrm{i}}\bar{\rho}_{\mathrm{i}} + \gamma_{\mathrm{c}}\bar{\rho}_{\mathrm{c}}^{\mathrm{FD}}\right) . \tag{7}$$

Above, $\bar{\rho}_{\mathrm{c}}^{\mathrm{FD}}$ denotes the average number of retransmission due to collisions in the case of full-duplex transmission*.

V. Collision and Interference Performance Analysis

In this section we compare the retransmission overhead and energy consumption of our proposed FD-CSMA/CD scheme with respect to CSMA/CA. First, Section V-A presents a general analysis, which is then specified for congested networks in Section V-B.

A. General case

Let us consider the energy savings of FD-CSMA/CD with respect to CSMA/CA, which is given by the difference between (1) and (7). This gives

$$\frac{\bar{\mathcal{E}}_{\mathrm{HD}} - \bar{\mathcal{E}}_{\mathrm{FD}}}{(P_{\mathrm{el,tx}} + P_{\mathrm{PA}})T_{\mathrm{b}}} = \bar{\tau}^{\mathrm{HD}} - \frac{\bar{\tau}_{\mathrm{d}} + \gamma_{\mathrm{i}}\bar{\rho}_{\mathrm{i}} + \gamma_{\mathrm{c}}\bar{\rho}_{\mathrm{c}}^{\mathrm{FD}}}{K}, \tag{8}$$

where $K = (P_{\mathrm{el,tx}} + P_{\mathrm{PA}})/(P_{\mathrm{el,tx}} + P_{\mathrm{PA}} + \alpha P_{\mathrm{rx}})$ is just a shorthand notation. Then, it can be seen that the FD-CSMA/CD scheme is more energy-efficient than CSMA/CA (i.e. $\bar{\mathcal{E}}_{\mathrm{HD}} - \bar{\mathcal{E}}_{\mathrm{FD}} > 0$) when the right hand side term of (8) is larger than zero, i.e.,

$$\bar{\tau}^{\mathrm{HD}} - \frac{\bar{\tau}_{\mathrm{d}} + \gamma_{\mathrm{i}}\bar{\rho}_{\mathrm{i}} + \gamma_{\mathrm{c}}\bar{\rho}_{\mathrm{c}}^{\mathrm{FD}}}{K} > 0 \ . \tag{9}$$

Rearranging (9) and using (2) gives

$$K < \frac{\bar{\tau}_{\mathrm{d}} + \gamma_{\mathrm{i}}\bar{\rho}_{\mathrm{i}} + \gamma_{\mathrm{c}}\bar{\rho}_{\mathrm{c}}^{\mathrm{FD}}}{\bar{\tau}_{\mathrm{d}} + \bar{\rho}_{\mathrm{i}} + \bar{\rho}_{\mathrm{c}}^{\mathrm{HD}}} \tag{10}$$

By defining the function $\Phi(N)$ as the right hand side of (10),

$$\frac{\bar{\tau}_{\mathrm{d}} + \gamma_{\mathrm{i}}\bar{\rho}_{\mathrm{i}} + \gamma_{\mathrm{c}}\bar{\rho}_{\mathrm{c}}^{\mathrm{FD}}(N)}{\bar{\tau}_{\mathrm{d}} + \bar{\rho}_{\mathrm{i}} + \bar{\rho}_{\mathrm{c}}^{\mathrm{HD}}(N)} := \Phi(N) \ , \tag{11}$$

it is straightforward to show that the condition $\bar{\mathcal{E}}_{\mathrm{HD}} - \bar{\mathcal{E}}_{\mathrm{FD}} > 0$ is equivalent to

$$K > \Phi(N) \ . \tag{12}$$

Note that $0 < K < 1$ and only depends on system parameters, being independent of the number of users.

Let us study the properties of $\Phi(N)$ for $N = 1$, i.e. when there is only one contending device and hence $\bar{\rho}_{\mathrm{c}}^{\mathrm{HD}} = \bar{\rho}_{\mathrm{c}}^{\mathrm{FD}} = 0$. If the interference from other networks is not important then $\Phi(1) \approx 1$, and as $K < 1$ then condition (12) is not attained. Therefore, in this case half-duplex transmissions are more energy-efficient than FD-CSMA/CD. On the other hand, if the network suffers from strong interference then $\Phi(1) = \gamma_{\mathrm{i}}$. If $K > \gamma_{\mathrm{i}}$, then the savings due to interference detection makes condition (12) to be attained for $N = 1$, and hence FD-CSMA/CD will be more efficient than CSMA/CA even for small networks with no collisions.

Let us now consider the case of dense networks, where N is large and hence the number of retransmission due to collisions becomes dominant. In general, full duplex experiences less collisions than half-duplex transmissions, i.e., $\bar{\rho}_{\mathrm{c}}^{\mathrm{HD}} \geq \bar{\rho}_{\mathrm{c}}^{\mathrm{FD}}$, as the reduction in collision time makes the medium less congested. Considering $\Phi(\cdot)$ as a continuous function, $\Phi(N)$ can be seen as a decreasing function with $\lim_{N\to\infty} \Phi(N) \leq \gamma_{\mathrm{c}}$. If $\Phi(1) > K$, then there exists a critical number of contending devices N^* which guarantee the following condition:

$$\Phi(N^*) = K \ . \tag{13}$$

Hence, the IBFD scheme will be more energy-efficient than CSMA/CA when there are more than N^* contending devices.

Let us end this subsection studying the energy savings that full duplex can provide for dense networks, where the condition $N \gg N^*$ is satisfied. By considering the ratio between (1) and (7) for large values of N, one can find that

$$\lim_{N\to\infty} \frac{\mathcal{E}_{\mathrm{T}}^{\mathrm{HD}}}{\mathcal{E}_{\mathrm{T}}^{\mathrm{FD}}} = \frac{K}{\gamma_{\mathrm{c}}} \lim_{N\to\infty} \frac{\bar{\rho}_{\mathrm{c}}^{\mathrm{HD}}}{\bar{\rho}_{\mathrm{c}}^{\mathrm{FD}}} > \frac{K}{\gamma_{\mathrm{c}}} > 1 \ . \tag{14}$$

As the asymptotic ratio is larger than 1, it can be seen that for the case of dense networks the rate of growth of $\mathcal{E}_{\mathrm{T}}^{\mathrm{HD}}$ with respect to N is larger than the one of $\mathcal{E}_{\mathrm{T}}^{\mathrm{FD}}$. This difference in growth rate implies that $\mathcal{E}_{\mathrm{T}}^{\mathrm{HD}} - \mathcal{E}_{\mathrm{T}}^{\mathrm{FD}}$ must also grow with N. This shows, in turn, that the energy savings of full duplex with respect to half duplex increase with the density of the network.

*As mentioned in Section I, the SNR does not change between half and full duplex and therefore $\bar{\tau}_{\mathrm{d}}$ remains the same.

B. Congested networks

Let us now focus on dense congested networks without hidden nodes, where the amount of data that each node needs to transfer is such that they will try to use the wireless channel as much as possible. In this case $\bar{\rho}_\mathrm{c}^\mathrm{HD} = \bar{\rho}_\mathrm{c}^\mathrm{FD} := \bar{\rho}_\mathrm{c}$, as the shorter collision time of full duplex does not reduce the traffic over the congested medium. Also, under this assumption the use of the shared medium by each contending device will not be affected by the channel fading statistics, and therefore the correlation between decoding errors and collisions can be neglected. Therefore, considering fast-fading conditions, then the Lemma presented in the Appendix shows that the total number of transmission trials can be expressed as

$$\bar{\tau} = (1-q_\mathrm{c})^{-1}(1-q_\mathrm{i})^{-1}(1-\bar{P}_\mathrm{f})^{-1} \ . \tag{15}$$

Above, q_c is the collision rate with packages from the same network, q_i is the rate of transmissions which experience interference from other networks given that there no collisions and $\bar{P}_\mathrm{f}$ is the mean frame error rate when the reception is done with no collisions and interference.

Let us study the relationship of q_i and q_c with $\bar{\rho}_\mathrm{i}$ and $\bar{\rho}_\mathrm{c}$. Following [17] (Sec II-B), one can identify $\bar{\tau}_\mathrm{d} = (1-\bar{P}_\mathrm{f})^{-1}$. Recall that $\bar{\rho}_\mathrm{i}$ and $\bar{\tau}_\mathrm{d}$ are independent of N, and that if $N=1$ then $\bar{\rho}_\mathrm{c}=0$ and $q_\mathrm{c}=0$. Hence, using (2) and (15) for the case of $N=1$, one can find that

$$\bar{\rho}_\mathrm{i} = \frac{1}{(1-q_\mathrm{i})(1-\bar{P}_\mathrm{f})} - \bar{\tau}_\mathrm{d} = \frac{q_\mathrm{i}}{(1-q_\mathrm{i})(1-\bar{P}_\mathrm{f})}. \tag{16}$$

Using again (2) and (15) for an arbitrary value of N, it can now be found that

$$\bar{\rho}_\mathrm{c} = \frac{1}{(1-q_\mathrm{i})(1-q_\mathrm{c})(1-\bar{P}_\mathrm{f})} - \bar{\tau}_\mathrm{d} - \bar{\rho}_\mathrm{i} \tag{17}$$

$$= \frac{q_\mathrm{c}}{(1-q_\mathrm{i})(1-q_\mathrm{c})(1-\bar{P}_\mathrm{f})}. \tag{18}$$

Note that a high frame error rate increases both $\bar{\rho}_\mathrm{c}$ and $\bar{\rho}_\mathrm{i}$, as it increase the number of times the frame needs to be radiated through the shared medium making it more vulnerable to collisions. In a similar way, a high probability of interference increases $\bar{\rho}_\mathrm{c}$.

Finally, using (16), (18) and (12) one can show that

$$\Phi(N) = (1-q_\mathrm{c})[(1-q_\mathrm{i})(1-\gamma_\mathrm{i}) + \gamma_\mathrm{i} - \gamma_\mathrm{c}] + \gamma_\mathrm{c} \ . \tag{19}$$

Considering the case $N=N^*$ and using (13), then from (19) one can find the following critical collision probability:

$$q_\mathrm{c}(N^*) = \frac{1-q_\mathrm{i}+q_\mathrm{i}\gamma_\mathrm{i}-K}{1-q_\mathrm{i}+q_\mathrm{i}\gamma_\mathrm{i}-\gamma_\mathrm{c}}. \tag{20}$$

This formula can be used for finding N^* for different MAC protocols, which determine a specific relationship between q_c and N. Let us consider a generic collision probability function given by

$$q_\mathrm{c}(N) = 1 - a\exp\{-bN^c\}, \tag{21}$$

which for specific values of a, b and c corresponds to the collision probability found in slotted or unslotted ALOHA, p-persistent CSMA and other common MAC protocols. Then, using (20), the critical number of nodes can be calculated directly as

$$N^* = \left(\frac{1}{b}\ln\frac{a(1-q_\mathrm{i}+q_\mathrm{i}\gamma_\mathrm{i}-\gamma_\mathrm{c})}{K-\gamma_\mathrm{c}}\right)^{1/c} \ . \tag{22}$$

It can be noted that if one decreases a, then q_c as given in (21) increases while N^* decreases. In a similar way, any change in the parameters a, b or c that makes q_c larger causes a decrease in the value of N^*. This suggests that the critical number of nodes N^* is smaller in networks with less efficient MAC solutions — i.e. networks with larger $q_c(N)$.

VI. Results

In this section we present numerical evaluations of the energy consumption of a node which uses the FD-CSMA/CD (Sec. IV-B) or CSMA/CA (Sec. IV-A) transmission schemes. The evaluations were performed using parameters corresponding to the IEEE 802.15.4 [18] and IEEE 802.11 [19] standards, and assuming that the node is part of a congested network. A 25dB SNR link was considered, resulting in $\bar{\tau}_\mathrm{d} = 2.2575$ for IEEE 802.15.4 and $\bar{\tau}_\mathrm{d} = 1.0101$ for IEEE 802.11. The collision probabilities where calculated according to the well-know model presented in [20] with corresponding values for CW_min and CW_max†. Table II shows these and all other parameters used in this section.

TABLE II
PARAMETERS USED FOR NUMERICAL EVALUATIONS

Parameter	IEEE 802.15.4	IEEE 802.11
Frame Header — L_H	13 bytes$^{||}$	50 bytes$^{\Phi}$
Payload length — L_P	127 bytes$^{||}$	1023 bytes$^{\Phi}$
Overhead — L_O	4 bytes$^{||}$	18 bytes$^{\Phi}$
Feedback frame length — L_F	11 bytes$^{||}$	20 bytes$^{\Phi}$
Bit per symbol — b	2$^{||}$	4$^{\Phi}$
Symbol rate — R_s	125 kS/s$^{||}$	9.75 MS/s$^{\Phi}$
Tx electronic power — $P_\mathrm{el,tx}+P_\mathrm{PA}$	30.67 mW*	824.4 mW§
Rx electronic power — $P_\mathrm{el,rx}$	35.28 MW*	212.4 mW§
Full duplex power ratio — α	0.7449$^{\diamond}$	0.7449$^{\diamond}$
Min. contention window — CW_min	8$^{||}$	32$^{\Phi}$
Max. contention window — CW_max	32$^{||}$	128$^{\Phi}$

From datasheet of: * TI CC2420, § TI CC3200. Source: ◇ [6], || [18], Φ [19].

Results confirm that the FD-CSMA/CD scheme provides important energy savings for dense networks (see Figure 3). The efficiency of FD-CSMA/CD is due to the lower energy cost of collisions, which allows a more graceful degradation of performance when the number of contending devices increases. For the case of no external interference ($q_\mathrm{i}=0$), CSMA/CA is more energy efficient for a low number of nodes. For a higher number of nodes, FD-CSMA/CD becomes better, the crossing point N^* is accurately predicted by (22), as can be seen from Figure 3. Also, as predicted in Section V-A, it

†Note that for IEEE 802.15.4 networks the model [20] works only as an approximation.

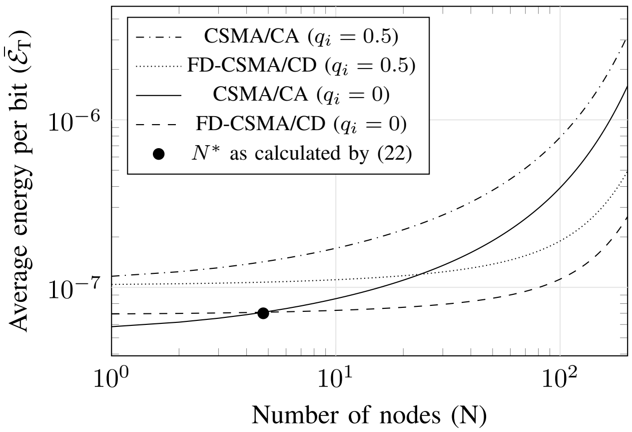

Fig. 3. Energy consumption of a wireless node per correctly transmitted bit, evaluated using (3) and (7) and considering parameters corresponding to the IEEE 802.11 standard.

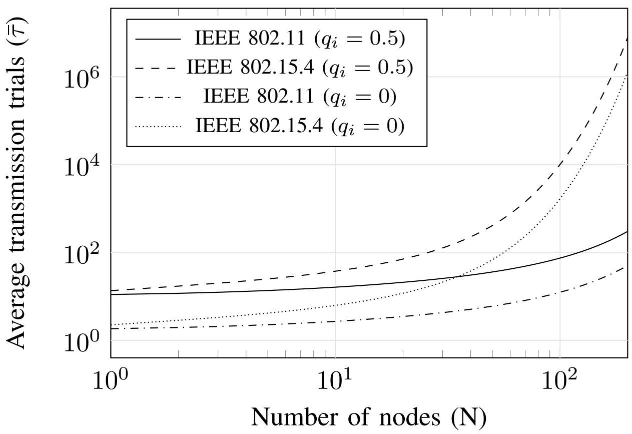

Fig. 4. Total number of transmission trials as given by (15). Collisions are a bigger problem in IEEE 802.15.4 than in IEEE 802.11, which is to be expected as the backoff period is much smaller in former.

can be seen that in the case of high interference (which in Figure 3 corresponds to $q_{\mathrm{i}} = 0.5^{\ddagger}$) the FD-CSMA/CD scheme is more efficient than CSMA/CA for all network sizes. This is expected as FD-CSMA/CD allows to conserve energy by aborting its transmission when interference is present.

Analogous results were found when the parameters of the IEEE 802.15.4 standard where used. Indeed, when comparing the average number of transmission trials for both standards (Figure 4), one can see that they are quite similar. Although not explicitly investigated, one could calculate from Figure 4 that due to a lower number of transmission trials, the overall throughput goes up. As more nodes can transmit new packets, instead of retransmitting old packets.

Finally, results show that N^* decreases when the amount of interference grows (see Figure 5). $N^* = 0$ means that full duplex is always more energy efficient. This supports the fact,

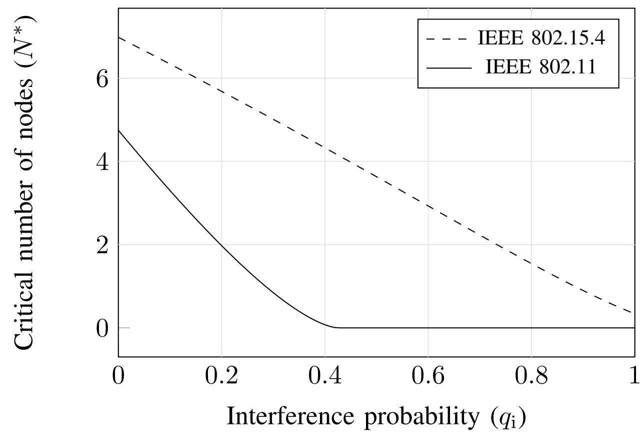

Fig. 5. The number of contending devices required for FD-CSMA/CD to become more energy-efficient than CSMA/CA decreases as the collision probability increases, in this case due to the growth of the interference.

already suggested by the analysis done on (22), that the FD-CSMA/CD scheme is more beneficial when the collision and interference statistics are more adverse.

VII. Conclusion

In this paper we analyze a novel FD-CSMA/CD scheme for dense wireless networks, which reduces the cost of retransmissions due to collisions or interference. For studying its energy efficiency, we develop an energy consumption model that reflects the strengths of the proposed scheme with respect to CSMA/CA transmissions.

Results showed that the proposed FD-CSMA/CD scheme is more energy-efficient than CSMA/CA for networks of any size if strong interference is present. In the case of low interference, the FD-CSMA/CD scheme is more efficient than CSMA/CA when the number of contending devices is above a critical value. We provide equations for finding this critical value, and showed that it decreases when the collision probability increases. For all the considered cases, the energy savings provided by the FD-CSMA/CD scheme grow with the density of the network.

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Appendix

Lemma: Suppose that a frame is transmitted repeatedly until it is decoded without errors by the receiver. During the j-th transmission trial, errors could be because of collisions with probability q_{c}, because of interference under the constraint of no collisions with probability q_{i} and because of decoding errors under the constraint of no collisions or interference with probability P_j, where P_j is a conditional probability for a given channel realization. Let us further assume fast-fading conditions, which is equivalent to the assumption than

‡This means that there is a failure due to interference in 50% of the packet transmissions. 50% was chosen to resemble an extreme case of interference, all practical values will be between 0% ($q_{\mathrm{i}} = 0$) and 50% ($q_{\mathrm{i}} = 0.5$).

$P_1, P_2, \ldots$ are i.i.d. Then, if τ denotes the number of trials until the transmission is successful, its mean value is given by

$$\bar{\tau} = (1-q_{\mathrm{c}})^{-1}(1-q_{\mathrm{i}})^{-1}(1-\bar{P}_{\mathrm{f}})^{-1} \ , \tag{23}$$

where $\bar{P}_{\mathrm{f}} = \mathbb{E}\{P_j\}$.

Proof: Let us define the following events:

$$\mathcal{C}_j = \left\{\text{no collisions during the } j\text{-th trial}\right\}, \tag{24}$$
$$\mathcal{I}_j = \left\{\text{no interference during the } j\text{-th trial}\right\}, \tag{25}$$
$$\mathcal{D}_j = \left\{\text{no decoding errors during the } j\text{-th trial}\right\}. \tag{26}$$

Then, one can calculate the following:

$$\mathbb{P}\left\{j\text{-th trial in error} \,|\, P_j\right\} = 1 - \mathbb{P}\left\{\mathcal{C}_j, \mathcal{I}_j, \mathcal{D}_j \,|\, P_j\right\} \tag{27}$$
$$= 1 - \mathbb{P}\left\{\mathcal{C}_j \,|\, P_j\right\}\mathbb{P}\left\{\mathcal{I}_j \,|\, \mathcal{C}_j, P_j\right\}\mathbb{P}\left\{\mathcal{D}_j \,|\, \mathcal{C}_j, \mathcal{I}_j, P_j\right\} \tag{28}$$
$$= 1 - (1-q_{\mathrm{c}})(1-q_{\mathrm{i}})(1-P_j) \ . \tag{29}$$

Let e_n be an indicator function, whose value is 1 if at least n trials were needed to achieve a successful transmitted frame and 0 otherwise (as $e_1 = 1$ we will focus on the case $n > 1$). The event $\{e_n = 1\}$ happens only if the $n-1$ previous trials were unsuccessful. As the channel realizations are given all previous attempts were independent events, and therefore for any $n > 1$ one finds that

$$\mathbb{P}\left\{e_n = 1 \mid \{P_j\}\right\} = \prod_{j=1}^{n-1} \mathbb{P}\left\{j\text{-th trial in error} \mid P_j\right\} \tag{30}$$
$$= \prod_{j=1}^{n-1} [1 - (1-q_{\mathrm{c}})(1-q_{\mathrm{i}})(1-P_j)]. \tag{31}$$

Note that $e_n \mid \{P_j\}_{j\in\mathbb{N}}$ is a Bernoulli random variable with parameter given by (30). As the expected value of a Bernoulli random variable is equal to its parameter, using (30), the definition of conditional expectation and the i.i.d. condition of the P_j, it can be shown that for any $n > 1$

$$\mathbb{E}\left\{e_n\right\} = \mathbb{E}\left\{\mathbb{E}\left\{e_n \mid \{P_j\}_{j\in\mathbb{N}}\right\}\right\} \tag{32}$$
$$= [1 - (1-q_{\mathrm{c}})(1-q_{\mathrm{i}})(1-\bar{P}_{\mathrm{f}})]^{(n-1)}. \tag{33}$$

Finally, the Lemma is proven by using the fact that $\tau = \sum_{n=1}^{\infty} e_n$ and (33):

$$\bar{\tau} = \sum_{n=1}^{\infty} \mathbb{E}\left\{e_n\right\} = \frac{1}{(1-q_{\mathrm{c}})(1-q_{\mathrm{i}})(1-\bar{P}_{\mathrm{f}})} \ . \tag{34}$$

References

[1] N. Bhushan, J. Li, D. Malladi, R. Gilmore, D. Brenner, A. Damnjanovic, R. Sukhavasi, C. Patel, and S. Geirhofer, "Network densification: the dominant theme for wireless evolution into 5g." *IEEE Communications Magazine*, vol. 52, no. 2, pp. 82–89, 2014.

[2] E. Obregon, K. W. Sung, and J. Zander, "On the sharing opportunities for ultra-dense networks in the radar bands," in *Dynamic Spectrum Access Networks (DYSPAN), 2014 IEEE International Symposium on*. IEEE, 2014, pp. 215–223.

[3] S. F. Yunas, M. Valkama *et al.*, "Spectral and energy efficiency of ultra-dense networks under different deployment strategies," *Communications Magazine, IEEE*, vol. 53, no. 1, pp. 90–100, 2015.

[4] S. Pollin, M. Ergen, S. Ergen, B. Bougard, L. Der Perre, I. Moerman, A. Bahai, P. Varaiya, and F. Catthoor, "Performance analysis of slotted carrier sense ieee 802.15. 4 medium access layer," *Wireless Communications, IEEE Transactions on*, vol. 7, no. 9, pp. 3359–3371, 2008.

[5] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proceedings of the sixteenth annual international conference on Mobile computing and networking*. ACM, 2010, pp. 1–12.

[6] T. Vermeulen and S. Pollin, "Energy-delay analysis of full duplex wireless communication for sensor networks," in *Global Communications Conference (GLOBECOM), 2014 IEEE*, Dec 2014, pp. 455–460.

[7] M. Jain, J. I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *Proceedings of the 17th annual international conference on Mobile computing and networking*. ACM, 2011, pp. 301–312.

[8] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in *ACM SIGCOMM Computer Communication Review*, vol. 43, no. 4. ACM, 2013, pp. 375–386.

[9] M. Chung, M. S. Sim, J. Kim, D. K. Kim, and C.-B. Chae, "Prototyping real-time full duplex radios," *arXiv preprint arXiv:1503.03013*, 2015.

[10] D. Nguyen, L.-N. Tran, P. Pirinen, and M. Latva-aho, "Precoding for full duplex multiuser mimo systems: Spectral and energy efficiency maximization," *Signal Processing, IEEE Transactions on*, vol. 61, no. 16, pp. 4038–4050, 2013.

[11] H. Alves, R. D. Souza, and G. Fraidenraich, "Outage, throughput and energy efficiency analysis of some half and full duplex cooperative relaying schemes," *Transactions on Emerging Telecommunications Technologies*, vol. 25, no. 11, pp. 1114–1125, 2014.

[12] G. Liu, H. Ji, F. R. Yu, Y. Li, and R. Xie, "Energy-efficient resource allocation in full-duplex relaying networks," in *Communications (ICC), 2014 IEEE International Conference on*. IEEE, 2014, pp. 2400–2405.

[13] S. Sen, R. R. Choudhury, and S. Nelakuditi, "Csma/cn: carrier sense multiple access with collision notification," *IEEE/ACM Transactions on Networking (TON)*, vol. 20, no. 2, pp. 544–556, 2012.

[14] F. A. Tobagi and L. Kleinrock, "Packet switching in radio channels: Part ii–the hidden terminal problem in carrier sense multiple-access and the busy-tone solution," *Communications, IEEE Transactions on*, vol. 23, no. 12, pp. 1417–1433, 1975.

[15] J. Peng, L. Cheng, and B. Sikdar, "A wireless mac protocol with collision detection," *Mobile Computing, IEEE Transactions on*, vol. 6, no. 12, pp. 1357–1369, 2007.

[16] F. Hermans, L.-Å. Larzon, O. Rensfelt, and P. Gunningberg, "A lightweight approach to online detection and classification of interference in 802.15. 4-based sensor networks," *ACM SIGBED Review*, vol. 9, no. 3, pp. 11–20, 2012.

[17] F. Rosas and C. Oberli, "Modulation and snr optimization for achieving energy-efficient communications over short-range fading channels," *Wireless Communications, IEEE Transactions on*, vol. 11, no. 12, pp. 4286–4295, 2012.

[18] "IEEE Standard for Local and metropolitan area networks–Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)," *IEEE 802.15.4-2011*, 2011.

[19] "IEEE Standard for Information technology–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE 802.11-2012*, 2012.

[20] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *Selected Areas in Communications, IEEE Journal on*, vol. 18, no. 3, pp. 535–547, 2000.